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ART. VI.—*Evaporation and Storage Changes in River Catchment Areas, with Special Reference to the Goulburn River, above Eildon Reservoir.*

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Abstract

Annual evaporation losses and storage changes in the river catchment areas of Victoria are discussed in relation to their effects upon the composition of natural waters. The river gauging and rainfall records of the Goulburn River catchment area, and other typical areas, were used as a basis for the investigation. Precipitation is the only source of water in the Goulburn catchment, which was selected to illustrate a useful method of approach. Underground leakage from this area is impossible. The composition of water from the Goulburn River is compared with waters from two adjoining areas—the Yarra River catchment, which is nearer the coast, and the more distant Murray River catchment.

Relationships between river flow and rainfall, under assumed ideal conditions, are contrasted with actual relationships disclosed on studying the river gaugings and rainfall records. No continuous run-off is yielded by Victorian catchment areas unless the annual rainfall is at least 13 inches, but the threshold rainfall of some rivers is 20 inches or more. River flow is diminished by direct evaporation, and by the transpiration of plants. Evaporation may continue after water is absorbed in the ground, but, ultimately, some absorbed water reaches the river system after being temporarily retained in the area. Seasonal gains and losses of underground water are always to be expected, and, also, there may be a net gain or loss over the whole year. Water carried over from year to year transforms an otherwise simple problem of interpreting results of river data into one of considerable complexity.

As the discussion is confined to areas free from underground leakage, observed discrepancies between river flow and precipitation must be attributed to the combined effects of evaporation, and storage changes. No direct methods are available for measuring evaporation, nor of ascertaining whether in a particular year the gauged flow was increased or decreased by storage changes. However, gains and losses can be eliminated by averaging long-period records, in which case mean evaporation is the difference between the mean precipitation and mean discharge for the period. But the problem of estimating evaporation and storage changes in a particular year has hitherto remained unsolved. The arguments presented in this paper are centred around the problem of eliminating, from the annual gauged flow of a river, uncertainties caused by the volume of water retained or released in the above-mentioned manner.

The data for the Goulburn area consists of 29 pairs of annual gaugings and rainfall records. The period of observations, although comparatively short, includes at least one complete major cycle of storage and depletion. When the ungrouped data are statistically correlated, the co-efficient ($r = +0{\cdot}9464$) indicates strong association between discharge and precipitation. The relationship may be expressed by a linear equation, $R_c = 0{\cdot}8626P - 16{\cdot}31$, the standard error of estimation is $2{\cdot}57$. Corresponding results for other catchment areas in Victoria are tabulated for purposes of comparison. Evaporation and storage changes can be estimated when, in addition to precipitation and the gauged discharge for a particular year, the computed flow is also known. Evaporation, estimated from the difference between precipitation and computed flow, increases as precipitation rises. Enhanced opportunities for evaporation at wet surfaces in years of higher rainfall may account for this regressional increase. Storage changes are estimated from the difference between the computed flow and the gauged discharge. Compound bar-charts and cumulative diagrams are employed to illustrate the effects of rainfall variations upon storage changes in the Goulburn area. The whole period may be divided into six sub-periods on the basis of these diagrams. Two phases of absorption or recharge are clearly recognizable, as well as two others during which stored water was being released from the catchment area. An important conclusion is that for seven successive years, during which correlation was exceptionally strong ($r = +0{\cdot}999$), climatic and other conditions were such that storage changes would not have been likely to occur; estimates of evaporation based on the data for this sub-period confirm those deduced from the data for the whole period. The results also indicate the possibility that the total upstream storage capacity of the Goulburn catchment area can be estimated. Although the investigation was carried out primarily in connection with the composition of natural waters, the results are of wider interest, and suggest new fields of inquiry.

Introduction

General Outline.

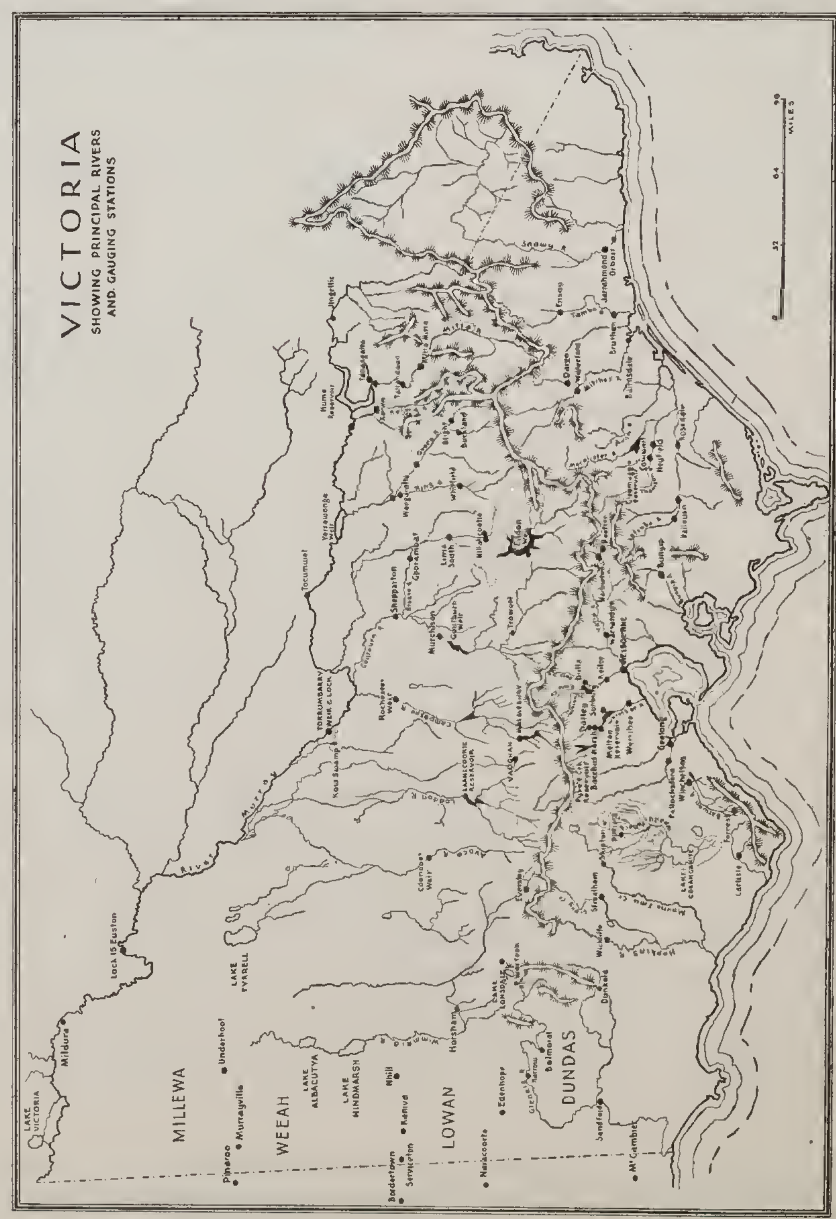
This study is an integral part of an investigation on relationships between the composition of natural waters and environmental conditions within the catchment areas from which the waters are derived. Evaporation and underground storage changes are the factors particularly under review in the present paper, estimates being based upon the results of river gaugings and rainfall observations published by the State Rivers and Water Supply Commission of Victoria(1). The catchment of the Goulburn River, above Eildon, in north-eastern Victoria, is used to illustrate a general method of approach, but a summary of the characteristics of other Victorian areas is included for purposes of comparison. The catchments investigated, unless otherwise indicated, are based upon impermeable bedrock, and each derives its water exclusively from meteoric sources within its own area.

The author has already shown that the principal sources of mineral impurities in Australian waters are (*a*) the soluble products of rock weathering, and (*b*) air-borne oceanic salts brought down in rain-water(2). The amount of contamination from the products of rock weathering depends upon the geological environment, but the proportion of oceanic salts brought to a catchment is, in general, independent of rock composition or structure, and is chiefly governed by geographical position.

Desiccated spray from sea-water is blown inland for great distances and in significant quantities, the movement of suspended particles even reaching the proportions of transcontinental dust-storms in reverse. Red dust from Central Australia is sometimes driven over the Tasman Sea. Not so well known is the fact that salt from the coast is carried by high winds to the interior of the Continent. The particles being soluble in water and almost invisible, their presence is often unsuspected unless rain-water is chemically examined, but probably every important catchment area in Australia is more or less influenced by this unseen transfer of oceanic salts.

The relatively low concentrations of sea-salts in rain-water may, at first sight, make them seem unimportant, but concentrations are greatly increased by natural evaporation and transpiration after the water reaches the ground. Records of river gaugings and rainfall show that, in Victoria, the average proportion of water removed by evaporation varies from 50 per cent. in exceptionally efficient catchments to 95 per cent. in useful, but inefficient, areas. In semi-arid regions the unevaporated residue, which still contains the soluble oceanic salts, is sometimes less than 1 per cent. of the rainfall. In addition to the effects of rock-weathering and the occurrence of air-borne salts in the rain-water, a third factor, evaporation, is thus equally important in determining the composition of natural waters in Australia, and a stage has now been reached when an improved method for estimating it is urgently needed.

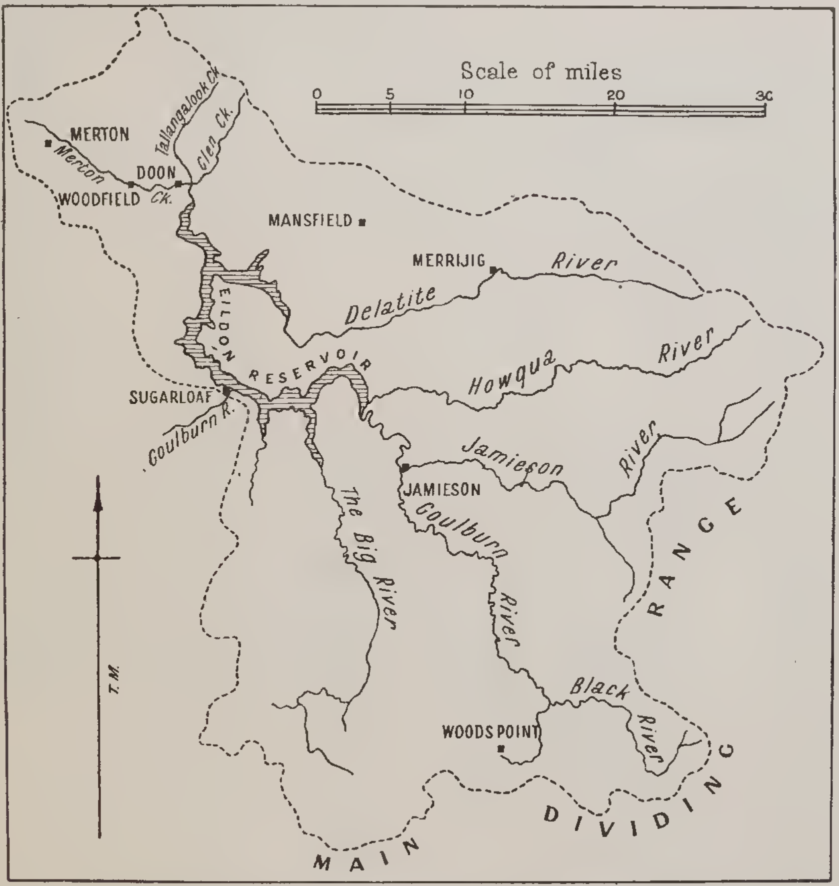
Storage also, above or below the surface, may affect the final composition of a natural water, otherwise than by providing opportunities for evaporation. Chemical changes of a secondary character, such as the biochemical oxidation of sulphur compounds, can occur during storage under aerobic conditions, but the anaerobic reduction of sulphates is a common occurrence during the underground storage or transfer of natural waters. Sulphates originally derived from oceanic sources can be completely removed from ground water in this way. Again, during the temporary storage underground, natural "softening" of a water sometimes takes place, calcium and magnesium being more or less completely replaced by chemically equivalent amounts of sodium or potassium. For various reasons, therefore, it is desirable to know how much of the rainfall in a particular year is temporarily stored in the ground, or alternatively, how much previously stored water is released to augment the flow of the river.



THE GOULBURN CATCHMENT AREA.

DESCRIPTION.

Situated on the northern slopes of the Main Divide, almost in the centre of the Eastern Highlands, the Goulburn catchment area is one of the most efficient in Victoria. The present capacity of the Eildon Reservoir is 306,000 acre-feet, but extensions are being planned. The geological map shows that the area of 1,500 square miles above Eildon consists almost entirely of slates and sandstones of Carboniferous, Devonian, Silurian, and Ordovician ages. There are also small isolated areas of igneous and granitic rocks. Maps published in the Reports of the Interstate Conference on Artesian Waters (1912-1928)(3) show that this catchment is part of an area in which no artesian basin of any material size can exist. Leakage of underground water into, or out of, the catchment is negligible, and influxes of magmatic and other types of juvenile water are extremely improbable. Apart from annual precipitation, and rain-water previously stored in the ground, no other source of water is available.



Map of Goulburn River Catchment Area above Eildon Reservoir.

The main axis of the catchment is approximately 90 miles from the coast. In relation to its distance from the sea, it occupies an intermediate position between two areas which have been described previously(2), viz., the Yarra River basin, and the valley of the Upper Murray River.

COMPOSITION OF RIVER WATER.

The waters of the above-mentioned rivers differ from each other considerably, but all have remained remarkably constant in composition for a long period. Typical results of analysis and other data are given in Table I.

TABLE I.—COMPARISON OF WATERS FROM THE YARRA, GOULBURN, AND MURRAY RIVER CATCHMENT AREAS.

CATCHMENT AREA DATA.	YARRA RIVER AT WARRANDYTE.	GOULBURN RIVER AT EILDON WEIR.		UPPER MURRAY RIVER AT TOCUMWAL.
Area (square miles)	972	1,500		10,234
Mean Annual Precipitation (inches) ..	44·61	39·59	27 years	33·19
Mean Annual Discharge (inches) ..	13·89	17·80		9·40
Mean Annual Evaporation (inches) ..	30·72	21·79		23·79
Percentage of Water Evaporated ..	68·9	55·0		71·7
CHLORIDES (Cl.) IN RAIN WATER.				
Milligrams per litre	4·4	2·9		1·0
Pounds per acre per annum	44·4	26·0		7·5
COMPOSITION OF RIVER WATER.				
MILLIGRAMS PER LITRE.				
Cl.	15·3	6·2		3·4
SO_4	1·6	1·9		1·3
HCO_3	14·3	27·8		23·0
NO_3	0·4	Nil		Trace
Ca	2·8	3·7		3·9
Mg	1·9	2·8		2·1
Na	8·5	4·6		2·4
K	1·7	1·5		1·0

POUNDS PER ACRE OF CATCHMENT AREA (ANNUALLY).

—	YARRA RIVER.		GOULBURN RIVER.		MURRAY RIVER.	
	Derived from Sea Water.	Not Derived from Sea Water.	Derived from Sea Water.	Not Derived from Sea Water.	Derived from Sea Water.	Not Derived from Sea Water.
Cl.	48·1	..	26·3	..	7·2	..
SO_4	5·0	..	3·60	4·5	1·0	1·8
HCO_3	0·4	44·6	..	118·0	..	48·9
NO_3	..	1·2	..	..	..	..
Ca	1·0	7·8	0·6	15·1	0·2	8·1
Mg	3·2	2·8	1·8	10·1	0·5	5·0
Na	26·7	..	14·6	5·0	4·0	1·1
K	1·0	4·3	0·55	5·8	0·1	2·0

Preliminary Discussion on Catchment Area Relationships.

PRECIPITATION AND DISCHARGE.

Precipitation on Victorian catchment areas is estimated from daily observations at a number of selected localities, the records from different stations being weighted to ensure that each locality is represented proportionately in respect of its area. The annual flows are computed from daily readings of river levels at specially selected gauging stations. Methods of procedure are described in River Gaugings (1905) and other reports.

Under ideal conditions, river discharge should equal precipitation. The annual gauged discharges (R) if plotted against the corresponding values for precipititation (P) might be expected to lie evenly along a straight line having its origin at the intersection of the R and P axes, and inclined at an angle of 45 degrees to the P axis (Figure 1. A–A¹). In practice, however, the annual discharge of a river is invariably less than precipitation, and the plotted values are often found to be widely dispersed in the form of a scatter diagram, such as that illustrated in Figure 1.

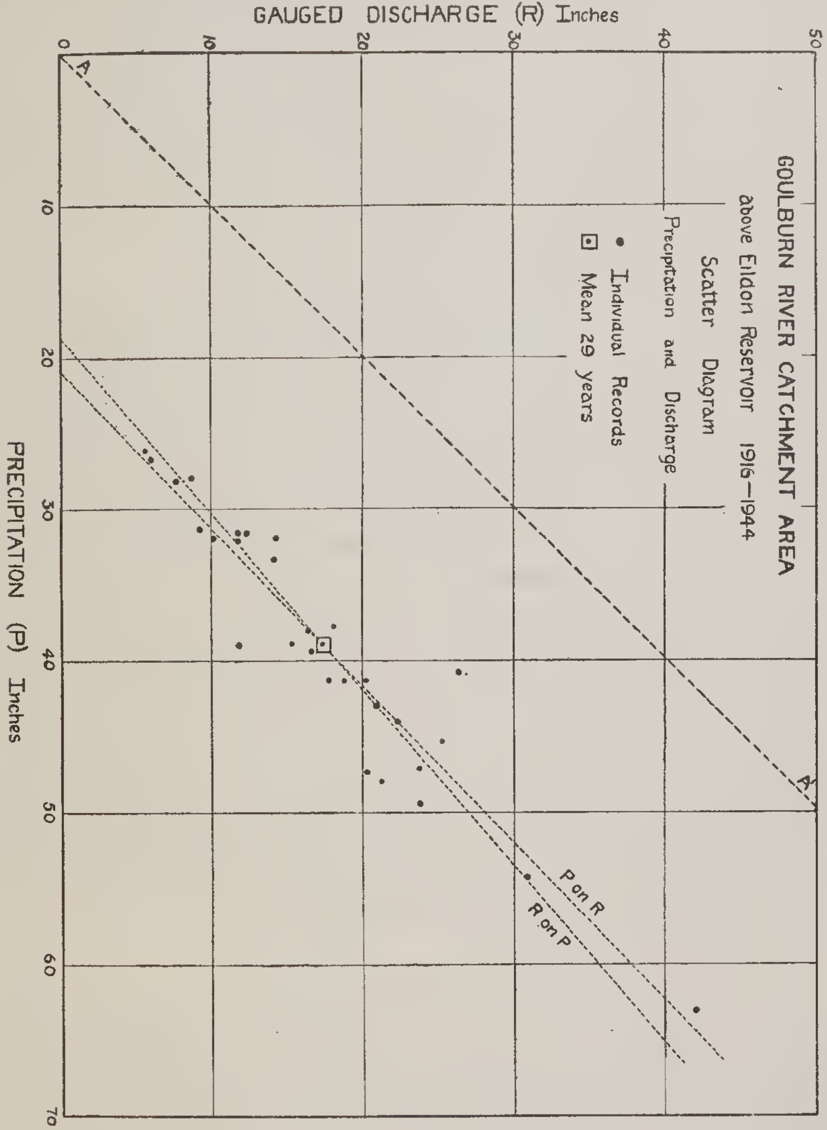


Fig. 1.

Precipitation is clearly the ultimate source of the discharged water, but the precise nature of the relationship between P and R is not immediately apparent from an inspection of the scatter diagram. One of the principal objects of this paper is to isolate the obscuring factors, especially evaporation and storage fluctuations, and then, as far as possible, to estimate the magnitude of each of them. This can only be done against a background provided by the catchment area equation, and with due regard to statistical principles.

Evaporation and Transpiration.

A substantial part of the rain-water falling on a catchment area is either directly evaporated or utilized by vegetation, and, in consequence, never reaches the river system. In the following discussion "evaporation" on a catchment area is intended to include transpiration. It is known that unless the mean annual precipitation exceeds a certain critical value, which may be called the threshold value, no continuous flow is yielded by catchment areas, although heavy rainstorms, or the release of ground water, may provide some run-off even in the driest years. The threshold values of Victorian catchments known to be enclosed by, and based upon impervious bedrock, range from 13 to 22 inches. Equality of precipitation and evaporation at the threshold value affords a basis for estimating the mean amount of evaporation which occurs under dry conditions, when the mean annual rainfall is just sufficient to cause incipient river flow.

STORAGE.

Much of the rain-water falling upon a catchment area soaks into the ground and becomes woven into the fabric of the vegetative and soil systems, including the underlying weathered rock material, before being released again in the form of seepages and springs, which finally drain into the river or its tributaries. Surface run-off from higher parts of a catchment area may be absorbed into the ground at lower elevations. Some water may remain in the ground for several years before actually reaching the river. If the water is accessible to the atmosphere, and to the roots of trees or other plants, losses by evaporation and transpiration may occur during storage. In the subsequent discussions, the use of the term " storage " is not restricted to ground-water below the water-table, but includes soil moisture and all other water, whether temporarily immobilized or moving towards the water-table, or to the outlets of the drainage system as a whole.

Seasonal variations in the volume of stored water are always to be expected; but, during a series of wet years the net amount of water stored in a catchment tends to increase at the expense of river flow. On the other hand, net depletion occurs in dry years, river flow being augmented. Variations in flow caused by daily and seasonal differences in the intensity or incidence of rainfall are automatically " smoothed out " in making the annual summations, but net changes for the annual period are not eliminated, and are responsible for part of the scatter illustrated in Figure 1, and they considerably add to the difficulty of interpretation.

THE CATCHMENT AREA EQUATION.

River flow is the greatly reduced residue from annual precipitation. Some water falling upon a river basin may be permanently lost by underground leakage to adjoining or distant areas; a large proportion is always lost by evaporation. River flow, in a particular year, may be diminished if water is temporarily retained in the area, or it may be supplemented by the release of water previously stored within the catchment.

An equation expressing relationships between precipitation (P), the gauged annual discharge (R), evaporation (E), and other factors influencing river flow, may be stated as follows:—

$$P = R + E + U + A \quad \ldots\ldots\ldots\ldots\ldots\ldots 1,$$

where U is the water lost by underground leakage, and A is the net increment to accumulated storage. The same symbol (A) is used, with changed sign, to represent a depletion of reserves previously stored within a catchment area.

The following discussion is simplified by confining it exclusively to catchment areas from which leakage is impossible, hence the equation may be written in the following form:—

$$P = R + E + A \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.$$

The practical value of this equation would be enhanced if direct measurements of either E or A could be made; but only in exceptional cases is this possible. However, the effects of storage variations may be eliminated by averaging long-period records of discharge and precipitation, gains in wet years being then offset by equivalent losses in other years. The equation may, therefore, be re-stated in a form which can be used for estimating the mean annual evaporation from a river basin:—

$$P_{\text{mean}} = R_{\text{mean}} + E_{\text{mean}} \quad \ldots\ldots 3.$$

Hitherto, the best available method for estimating evaporation was based upon equation 3. Such estimates, however, correspond only to a particular value of P, viz., P_{mean}, and afford no information about the amount of evaporation occuring when precipitation is above or below its mean value. It will be shown later that, by appropriate methods, it is possible to develop an equation for computing values of river flow which are not only free from the disturbing effects of storage variations, but are applicable to any corresponding value of precipitation within the observed range. Computed flows from which storage variations have been eliminated are conveniently designated by the symbol R_c to distinguish them from the gauge discharge (R), the relation between R_c and R being as follows:—

$$R_c = R + A = P - E \quad \ldots\ldots 4.$$

The general equation is then simplified to—

$$P = R_c + E. \quad \ldots\ldots 5.$$

On investigating the precipitation and discharge records of 25 catchment areas in Victoria, the author has found that a simple linear relationship exists between R_c and P, which may be expressed as follows:—

$$R_c = a + bP \quad \ldots\ldots 6.$$

The constants a and b may be calculated from long-term records of river gaugings and precipitation, and the equation used for estimating R_c and E for any value of P within the range covered by the data. The fact that linear equations satisfactorily express precipitation-discharge relationships of catchment areas in Victoria considerably reduces the labour involved in making computations of this kind. It is conceivable, however, that for some catchment areas the use of polynomial equations may be necessary.

Statistical Treatment

THE GOULBURN DATA.

The relatively small number of records available for statistical examination consists of 29 pairs of official observations of rainfall and river gaugings, the latter being adjusted for volumes released or impounded, and for evaporation in the reservoir. The frequency curve of annual precipitation is very flat, but it discloses a normal distribution during the perod of 1916-1944. Estimates of skewness indicate only a slight degree in the rainfall records, and a rather more pronounced degree in the discharge data; but, for practical purposes, both distributions may be regarded as sufficiently symmetrical to provide a basis for treatment by ordinary statistical methods.

Some doubt may exist as to whether observations over a period of 29 years are sufficiently representative to eliminate systematic errors due to long-term cycles of charge and recharge. In general, it is desirable to use at least 40 pairs of annual observations, unless it can be shown that a shorter period includes at least one complete cycle of storage changes, or there is a reasonable expectation that the volume of water stored in the catchment area was substantially the same at the end of the period as at its commencement. As a long drought period immediately preceded the year 1916, it may be inferred that the Goulburn area was in the same depleted condition prior to 1916 as it was at the end of 1944. Notwithstanding, therefore, the relative shortness of the period of observations, the wide ranges of precipitation and discharge in this catchment area, and the certainty that leakage can be excluded, make it particularly suitable for illustrating a method of approach which is applicable to the majority of other river basins in Victoria.

CORRELATION.

An appropriate method of treatment is to correlate discharge data with annual precipitation over all individual pairs, regarding complexities due to changes in underground storage, and sundry random errors, as a group of uncontrollable deviations. The correlation co-efficient (r), and the constants of the equation relating discharge and precipitation are computed, and the standard error of estimation is calculated. It is then possible, against the background of the catchment area equation, to deduce some quite definite information about the relationship between precipitation and evaporation. Net annual gains and losses in underground storage are estimated as the difference between the computed and gauged discharges. This method may require modification and elaboration in the light of additional information, but, even in its present form, it greatly assists in clarifying the various issues and relationships.

The catchment area data, with relevant extensions and derivations, are ranked on the basis of annual precipitation, and set out in Table II.

TABLE II.—THE GOULBURN RIVER CATCHMENT AREA, ABOVE EILDON WEIR.

Correlation of Precipitation and Discharge Data (1916–1944), *showing Computed Evaporation, and Estimated Storage Changes* (*in Inches*).

1.	2.	3.	4.	5.	6.	7.	
Year.	Precipitation (P).	Discharge. (R).	Difference. (P—R).	Computed Discharge (R_c).	Computed Evaporation (E).	Estimated Storage Changes ($R—R_c$).	
						Storage.	Depletion.
1938 ..	26·2	5·6	20·6	6·3	19·9	0·7	..
1940 ..	26·7	6·0	20·7	6·7	20·0	0·7	..
1944 ..	28·1	8·6	19·5	7·9	20·2	..	0·7
1937 ..	28·3	7·7	20·6	8·1	20·2	0·4	..
1922 ..	31·4	9·3	22·1	10·8	20·6	1·5	..
1925 ..	31·6	12·4	19·2	10·9	20·7	..	1·5
1927 ..	31·6	11·9	19·7	10·9	20·7	..	1·0
1919 ..	32·0	10·1	21·9	11·3	20·7	1·2	..
1943 ..	32·0	14·4	17·6	11·3	20·7	..	3·1
1929 ..	32·1	11·6	20·5	11·4	20·7	..	0·2
1933 ..	33·4	14·3	19·1	12·5	20·9	..	1·8
1932 ..	36·9	18·2	18·7	15·5	21·4	..	2·7
1936 ..	38·2	16·5	21·7	16·6	21·6	0·1	..
1930 ..	38·9	15·4	23·5	17·2	21·7	1·8	..
1941 ..	39·1	11·9	27·2	17·4	21·7	5·5	..
1934 ..	39·5	16·6	22·9	17·8	21·7	1·2	..
1931 ..	40·8	26·4	14·4	18·9	21·9	..	7·5
1926 ..	41·3	20·2	21·1	19·3	22·0	..	0·9
1920 ..	41·4	17·9	23·5	19·4	22·0	1·5	..
1921 ..	41·4	18·8	22·6	19·4	22·0	0·6	..
1918 ..	43·0	21·0	22·0	20·8	22·2	..	0·2
1935 ..	44·1	22·2	21·9	21·7	22·4	..	0·5
1942 ..	45·3	25·2	20·1	22·8	22·5	..	2·4
1923 ..	47·1	23·7	23·4	24·3	22·8	0·6	..
1924 ..	47·4	20·3	27·1	24·6	22·8	4·3	..
1928 ..	48·0	21·2	26·8	25·1	22·9	3·9	..
1916 ..	49·5	23·9	25·6	26·4	23·1	2·5	..
1939 ..	54·3	30·6	23·7	30·5	23·8	..	0·1
1917 ..	63·0	42·0	21·0	38·0	25·0	..	4·0
Total ..	1,132·6	503·9	628·7				
Mean ..	39·06	17·38	21·68	*Correlation Coefficient*, (r) = 0·9464 *Constants of estimating equation* ($R_c = a + bP$) a = −16·31 b = 0·8626 *Standard Error of Estimation* 2·57			
Standard Deviation	8·74	7·96	2·84				

THE REGRESSION OF RIVER DISCHARGE ON PRECIPITATION.

The co-efficient of correlation ($r = +0 \cdot 9464$) indicates a very close association between annual precipitation and river flow over the range of the available observations. Although the association is strong, the estimating equation accounting approximately for 90 per cent. of the total variance of the discharge data, a decision had to be made respecting the basis on which the regression should be calculated, that is to say, whether P or R was to be regarded as the independent variable. In any case, the two possible regression lines are not widely divergent (see Fig. 1), but, as river flow in this catchment is known to depend primarily upon water from meteoric sources, the choice of precipitation as the independent variable is appropriate.

The constants for the Goulburn catchment area are as follows:— $a = -16 \cdot 31$, $b = 0 \cdot 8626$. "b" represents the rate of change of river flow per unit of precipitation in the absence of random deviations. Expressed graphically, "b" corresponds to the slope of the straight line indicating the regression of R_c on P, while "a" specifies the point of origin on the R axis. R_c may be regarded as the volume of river flow which, in any year, would be directly caused by precipitation in that year, if there were no storage changes or other random deviations. In the known absence of leakage the constants "a" and "b" are related to, and are to be regarded as corrections for, the amount of evaporation which occurs in the catchment. The ratio $\frac{o - a}{b} = 18 \cdot 91$ indicates the point ($R_c = o$) at which the regression line intersects the P axis, and, therefore, specifies the computed mean threshold precipitation, below which all of the rainfall would be evaporated, leaving no surplus for river flow. A correction for any additional loss by evaporation of rainfall in excess of the threshold value is made by multiplying by $1 - b$. The equation for the Goulburn River catchment may be expressed in the following alternative form, in which R_c is estimated by multiplying the regression co-efficient (b) by the difference between the mean threshold value and total precipitation:—

$$R_c = 0 \cdot 8626\ (P - 18 \cdot 91) \ldots\ldots\ldots\ldots\ldots\ldots 7.$$

It is one of the basic assumptions of the present method of approach that dependable estimates of R_c can be made even when losses by evaporation, and fluctuations in storage, are known to occur from year to year. Individual values of the gauged discharges do not appear in the estimating equation, but the whole of the available data is used in the statistical procedure for computing the constants of the equation. In this respect R_c is hardly less important than the mean discharge, and possesses the additional advantage that it can be computed for any observed annual precipitation, whereas R_{mean} corresponds only to the mean precipitation for the whole period.

It will be observed by reference to Table III. (column 8) for Victorian catchment areas, the constant (b) is always significantly less than unity.

THE REGRESSION OF EVAPORATION ON PRECIPITATION.

The difference between precipitation and the gauged discharge may be regarded as a crude estimate of evaporation in a catchment area during a particular year; but the effects of storage changes must be eliminated to obtain the true evaporation. The most direct method for estimating E is, therefore, to subtract the computed discharge (R_c) from precipitation (P).

TABLE III.—TYPICAL CATCHMENT AREAS IN VICTORIA.

Correlation Data.

1.	2.	3.	4.	5.	6.	7.	8.		9.	10.
Catchment Area.	Gauging Station.	Area. (Square Miles.)	Period of Observations. (Years.)	Mean Annual Precipitation (P). (Inches.)	Mean Annual Discharge (R). (Inches.)	Correlation Coefficient. (r) +	Constants of Estimating Equation ($R_c = a + bP$).		Standard Error of Estimation.	Computed Threshold Precipitation. $\frac{o - a}{b}$
							a −	b +		
(1) NORTH OF DIVIDE.										
(a) *North-Eastern.*										
Goulburn	Eildon Weir	1,500	29	39·06	17·38	0·946	16·31	0·8626	2·57	18·91
Murray	Jingellic	2,520	52	37·54	13·86	0·896	10·11	0·6386	2·66	15·83
Mitta	Tallangatta	1,990	50	37·44	10·88	0·879	10·31	0·5660	2·38	18·22
Ovens	Wangaratta*	2,090	50	42·86	10·75	0·813	10·70	0·5005	3·39	21·38
Broken	Goorambat*	730	50	31·68	5·65	0·829	10·75	0·5092	2·27	21·11
Kiewa	Kiewa	434	51	50·37	23·77	0·649	9·97	0·6691	8·58	14·90
(b) *Central.*										
Coliban	Malmsbury	112	50	35·08	8·96	0·833	10·58	0·5571	2·64	18·99
(c) *North-Western.*										
Loddon	Laanecoorie	1,592	46	24·35	2·20	0·819	4·23	0·2637	2·86	16·04
Avoca	Coonooer	1,029	41	19·46	1·05	0·839	2·31	0·1725	0·49	13·40
(2) SOUTH OF DIVIDE.										
(a) *South-Eastern.*										
Yarra	Warrandyte	972	23	44·61	13·88	0·864	12·11	0·5827	2·18	20·78
Tambo	Bruthen	1,040	19	27·84	3·83	0·830	5·73	0·3433	1·37	16·70
(b) *Central.*										
Maribyrnong	Keilor	550	26	28·12	3·00	0·849	6·43	0·3355	1·16	19·16
(c) *Western.*										
Barwon	Pollocksford	1,425	15	25·33	1·91	0·923	3·37	0·2087	0·37	16·15
Woady Yallock	Pitfield	122	15	26·40	3·30	0·696	8·82	0·4591	1·61	19·21
Glenelg	Sandford	3,320	20	25·85	3·40	0·817	9·20	0·4876	1·35	18·87
Glenelg	Balmoral*	606	45	25·93	3·56	0·693	6·36	0·3830	1·84	16·61

* The possibility of slight leakage cannot be excluded.

Applying this method to the Goulburn catchment area for different values of P, the following typical results are obtained:—

TABLE IV.—GOULBURN RIVER—CATCHMENT.

The Regression of Evaporation on Precipitation.

Precipitation. (P)	Computed Discharge. (R_c)	Evaporation. (E)
18·9 (threshold)	0·0	18·9
26·2 (lowest)	6·3	19·9
39·1 (mean)	17·4	21·7
52·4 (relatively high)	28·9	23·5

Evaporation increases progressively with precipitation and discharge, but its range of variation is much less. This indication that evaporation in the catchment area is insensitive to changes in precipitation is of importance when considering the accuracy with which evaporation can be estimated. There is a significant correlation ($r = +0{\cdot}423$) between precipitation and crude evaporation estimated as the difference between P and R. The relationship between P and E in the Goulburn area may be expressed as follows:—

$$E = 0{\cdot}137\,P + 16{\cdot}3.$$

At Melbourne, total evaporation from a free water-surface is usually less in wet than in dry years. A significant inverse correlation ($r = -0{\cdot}403$) was found between the rainfall and total evaporation at Melbourne, when the records covering a period of 68 years (1877-1944) were investigated. But the converse is true of evapo-transpiration in Victorian catchments. This regressional increase of evaporation on precipitation in catchment areas is difficult to explain, except by assuming that additional opportunities for evaporation occur in years of higher rainfall.

It will already have been noticed that the regression co-efficient of discharge on precipitation ($b = 0{\cdot}863$) accounts only for 86·3 per cent. of the rainfall, even after making due allowance for the loss by evaporation which is known to occur before any of the water is available for river flow. Permanent leakage from the catchment would explain the inadequacy of the regression co-efficient to account for the whole of the rainfall in excess of the threshold value, but leakage from this catchment is impossible owing to the impermeable nature of the underlying and enclosing rocks. On the other hand, a regressional increase in evaporation is by no means unlikely, because, in Central Victoria, the mean threshold value corresponds with an evaporation equal only to one-half of the total annual evaporation from a free water-surface. The threshold evaporation does not, therefore, exhaust the evaporative possibilities of the local climate. Opportunities for evaporation at wet surfaces might be expected to be greater during years of abundant rainfall, compared with the necessarily limited opportunities available in dry years. Transpirational losses are also greater in "good" years, when vegetative growth is heavier.

The regression of evaporation on precipitation is compared with that of discharge in Figure 2.

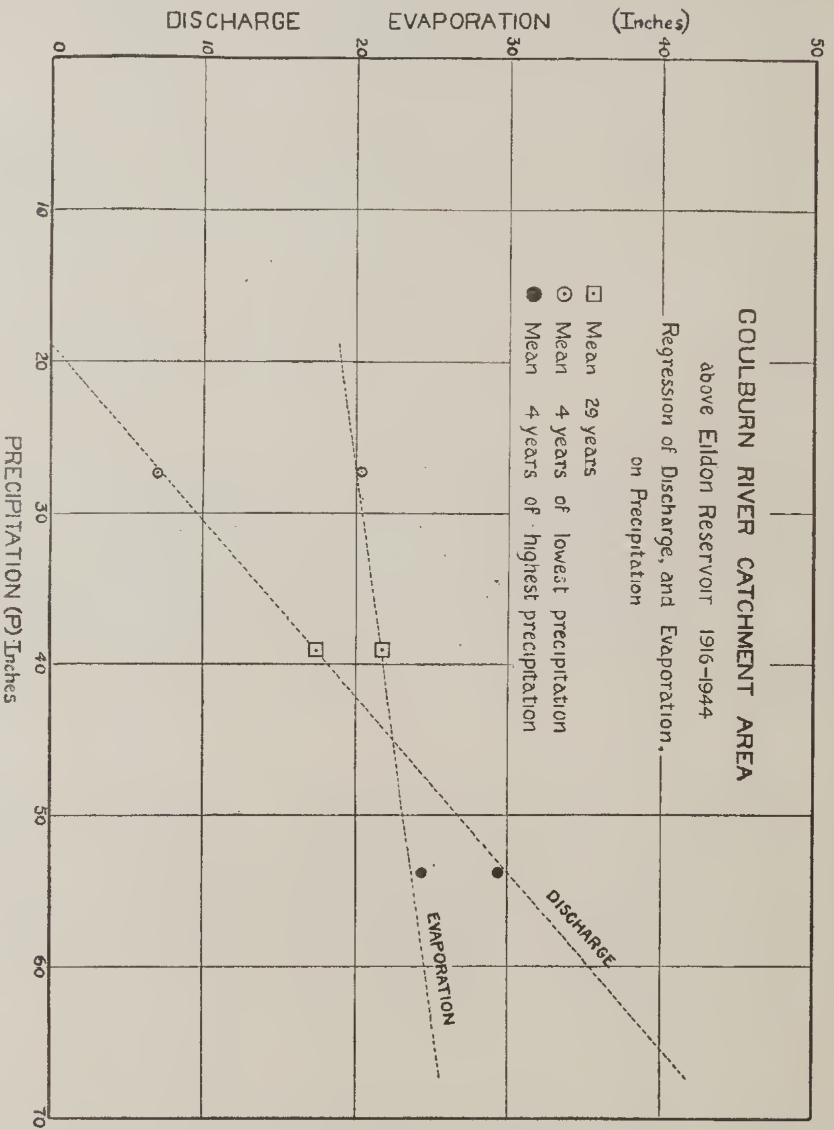


Fig. 2.

The Residual Variance.

Changes in ground-water storage can sometimes be estimated by observing the water levels of wells and lakes. Measurements have been made at Blue Lake, Mt. Gambier (S.A.), where the surrounding country is comparatively flat, and the porous Tertiary limestone permits rapid readjustment of the lake level to changes in the ground-water table. It seems doubtful, however, whether any analogous method could be usefully applied in the mountainous catchment area of the Upper Goulburn River, but estimates of storage changes can be made by comparing the gauged discharge (R) of the river with the computed discharged (R_c). The difference between R and R_c is regarded as an estimate of net storage or depletion. As a first approximation, it may be accepted that increments and decrements of stored water are responsible for the whole of the difference between R and R_e. Two assumptions are involved—the first is that if no storage changes occurred, the relationship between precipitation and discharge would be strictly a linear one; the second is that deviations due to storage changes, if they do occur, will be normally distributed about the regression line. The reliability of the estimate obtained by difference in this way depends, of course, upon the degree of accuracy with which (R_e) can be estimated, as well as upon the reliability of the river gaugings.

The assumption that storage changes are responsible for the residual variance is sufficiently well-founded to warrant its adoption as a working hypothesis, pending further investigation. In the catchment of the Avoca River, where storage changes are known to be small, residual variance is relatively low. It was also exceptionally low in the Goulburn area for seven successive years, when precipitation was not high enough to recharge this catchment, which had become depleted during three preceding dry years. A comparison of the characteristics of the Avoca and Goulburn catchment areas is of considerable interest in this connexion.

In the mountainous areas of Eastern Victoria, climatic and physiographic conditions are favourable to storage changes, which normally manifest themselves in large perennial streams. Opposite conditions prevail in north-western Victoria, particularly in the catchment of the Avoca River where the terrain is relatively flat, and the mean annual rainfall is only 19·46 inches (maximum, 28·0). Depletion can occur only from a previously charged catchment area, and a depleted catchment can only be recharged during periods of relatively high rainfall. It is unlikely that, in the Avoca catchment area, precipitation is sufficient, even in wet years, to allow any appreciable surplus of stored water to be carried over from year to year, after evaporative demands have been met. Net storage changes are, therefore, at a minimum, although not completely absent, and the river is semi-intermittent in character. Over a period of 41 years the standard deviation of R was relatively low (0·90), compared with that for the Goulburn catchment area (7·96). In these circumstances poor correlation seemed inevitable, but the association between precipitation and discharge is strong, owing to a corresponding decrease in residual variance, the standard error of R_e for the Avoca area being 0·49, which is less than one-fifth of that computed from the Goulburn River records for 29 years (2·57).

Included in the Goulburn records, there is a period of seven years during which the catchment area remained in a depleted condition after an earlier dry period. Precipitation in the preceding three years was relatively low, although river flow was comparatively high, indicating a phase of depletion. Precipitation during the sub-period under review (1934-1940) was variable, but the average (36·76) was below the mean for 29 years (39·06), and obviously insufficient to recharge the depleted catchment area. Correlation of precipitation with discharge was unusually high ($r = +0 \cdot 999$), the linear relationship being represented by the following equation:—

$$R_e = 0 \cdot 892\, P - 17 \cdot 7.$$

The standard error of estimation is 0·40. When this equation is used to predict the discharge of the Goulburn River, corresponding to the mean precipitation for 29 years (39·06 inches), the estimate (17·1 inches) is not significantly different from the mean discharge (17·4 inches) for 29 years. The predicted threshold value is 19·9 inches, compared with 18·9 inches, the value predicted by the equation computed from the data for 29 years. Strong correlation alone does not necessarily indicate the absence of net storage changes, because it is conceivable that, during the sub-period, the area may have been either gaining or losing water at a uniform annual rate. However, the close correspondence between the constants of the equation for the sub-period, and those computed for the period of 29 years, practically excludes both possibilities. Although a slight storage trend is indicated when the results for seven years are aligned with those for the whole period, they are consistent with the view that the shorter period was one in which there was no significant increase or decrease in storage. Obviously, the whole problem is simplified when periods substantially free from storage changes are available as a basis for estimating evaporation.

General Discussion of Results

STORAGE AND DEPLETIONARY TRENDS.

Annual variations in precipitation, river flow, estimated evaporation, and storage changes, for the period under review, are illustrated in a group of compound bar-charts (fig. 3).

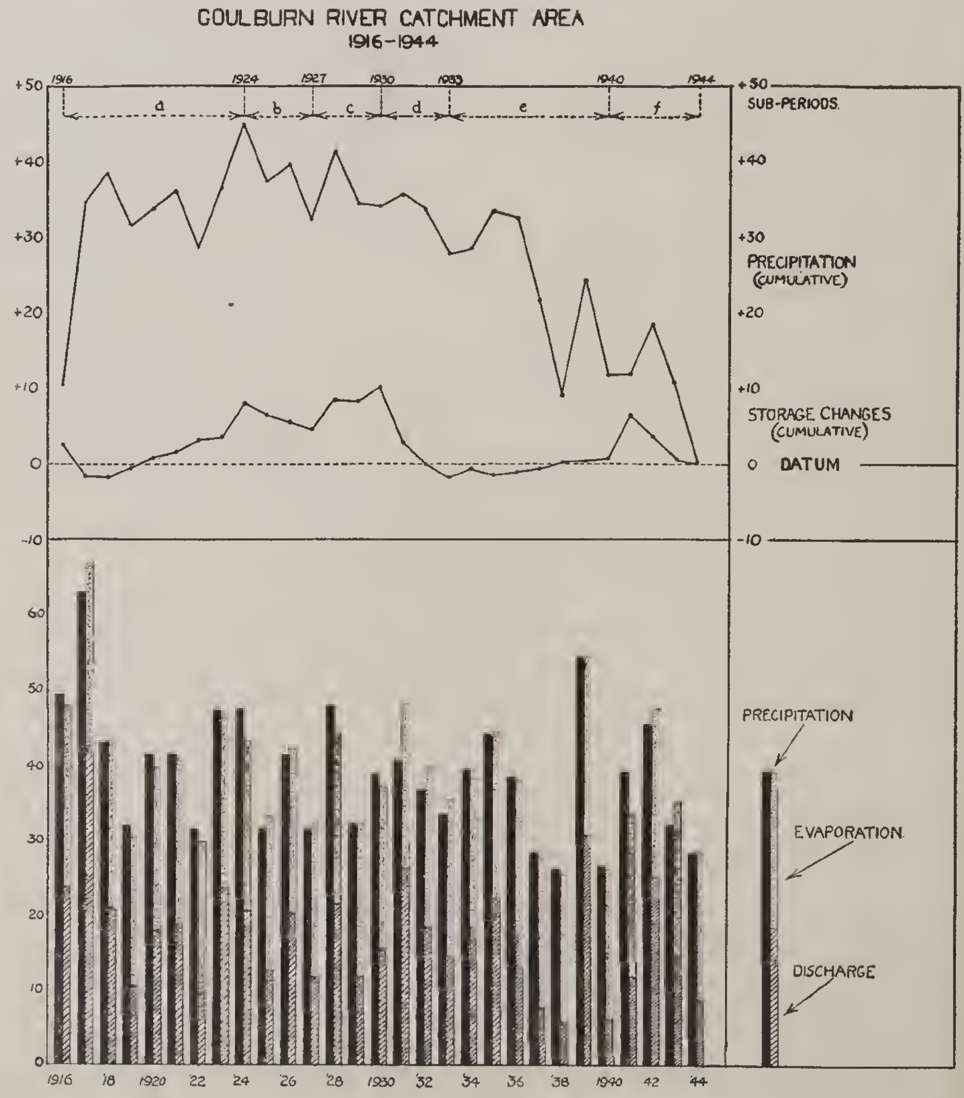


FIG. 3.

This diagram shows whether, apart from seasonal variations, water was stored in, or released from, the catchment area during a particular year. Conclusions indicated are consistent with some well-established facts concerning the storage of water in catchment areas, and explain some apparent anomalies in discharge phenomena. They also suggest several new fields of inquiry.

The general tendencies discernible in this diagram may be summarized as follows:—

(*a*) Water is stored in a catchment area during cycles of high average rainfall. An occasional dry year does not always alter the general trend, unless a considerable amount of water has already been accumulated in the catchment area.

(*b*) Depletion of water from a charged catchment occurs during periods of low average rainfall. A single wet year does not necessarily alter a general depletionary trend.

(*c*) The amount of stored water tends to remain constant from year to year when a period of depletion is soon followed by a further dry period. More than one wet year may be required to alter this tendency, which, along with others, is more clearly illustrated in the cumulative diagram (fig. 3).

There are also indications, yet to be confirmed, that floods and other catastrophic phenomena facilitate the release of water from charged catchments, possibly by eroding new seepage channels or by removing natural barriers which would otherwise retard the escape of water.

Modified mass or cumulative diagrams, despite obvious disadvantages, are particularly useful for illustrating storage changes in catchment areas. The datum of the cumulative rainfall diagram is the mean annual precipitation for the whole period, deviations from the mean being plotted cumulatively. Estimated gains and losses of stored water are also plotted cumulatively in a second diagram. On comparing the two charts, several periods of release and recharge, as well as the relatively constant period, are recognizable, together with corresponding variations in rainfall. On the basis of these diagrams, the period under review may be divided into the six sub-periods shown in Table IV.

TABLE IV.—GOULBURN CATCHMENT AREA. 1916–1944.

Sub-Periods of Release and Re-charge.

Sub-periods.			Mean Precipitation (Inches).	Mean Discharge (Inches).	Net Gain or Loss during Sub-periods.	
——	Number of Years.	General Trend.			(Inches.)	Acre/feet on Whole Area.
(*a*) 1916–24 ..	9	Re-charge ..	44·0	20·8	+8·0	+640,000
(*b*) 1925–27 ..	3	Release ..	34·8	14·8	−3·3	−260,000
(*c*) 1928–30 ..	3	Re-charge ..	39·7	16·1	+5·5	+440,000
(*d*) 1931–33 ..	3	Release ..	37·0	19·6	−12·0	−960,000
(*e*) 1934–40 ..	7	Approximately constant	36·7	15·0	+2·6	+210,000
(*f*) 1941–44 ..	4	Variable ..	36·1	15·0	−0·8	−64,000
1916–44 ..	29	..	39·06	17·38	..	..

APPARENT ANOMALIES.

Some apparent anomalies may be explained with the aid of the diagrams. For example, during three years commencing in 1928, (c) the average discharge (16·1 inches) of the Goulburn area was lower than in the following three years (19·6 inches), notwithstanding the higher average rainfall (39·7 inches) during the former period, compared with the rainfall (37·0 inches) of period (d). To explain this anomaly in terms of evaporation changes would involve the highly improbable assumption that the average annual loss by evaporation in one period was 6·2 inches greater than in the other. The average difference in evaporation estimated from the regression of E on P was only 0·4 inch. It has already been shown that evaporation is much less variable than either precipitation or discharge. The explanation indicated by these diagrams is that during sub-period (c) appreciable amounts of water were retained in the catchment at the expense of river flow, while in the three following years of diminishing rainfall the flow of the river was augmented by water released from the catchment. This is not an isolated case, but is quite typical of many examples which could be cited from other catchment areas in Victoria.

Sub-period (e) during which, as previously described, only slight changes in stored water occurred, except possibly for seasonal variations, is also typical of the behaviour of other river catchments during periods of low average rain following an earlier dry period. Apparently a state of equilibrium was reached, beyond which further augmentation of river flow by ground-water was impossible.

EVAPORATION DURING STORAGE.

Evaporation and storage conditions in catchment areas are closely related, and both have important effects upon the quality of river waters. The effects of evaporation can be recognized and estimated by observing changes in the concentration of chlorides originally present in the rain-water. In the Eastern Highlands, springs and seepages feeding the mountain-tract tributaries of river systems, yield waters containing very low concentrations of chlorides. A marked increase is usually observed before the streams emerge into larger river valleys. Progressive increases in chlorides are found in tributaries which enter the main stream from open plains. It is often supposed that the higher chlorinities of the lower reaches of a river are due to the ocean, but the same tendency is noticeable in some rivers north of the Main Divide, and which flow away from the coastline. Greater opportunities for evaporation in the open plains account for this increase in salinity.

It is well known that the dry-season flow of rivers is often more saline than the flow in wet seasons. But the author has observed that the chlorinities of some river waters, in Victoria, are definitely lower during dry seasons. The waters of the Yarra River, and of other Victorian streams, contain a higher proportion of chlorides in winter than in summer. After prolonged droughts, the Yarra water is consistently lower in dissolved solids. Storage conditions explain this unexpected effect on river waters in Eastern Victoria. Ground-water temporarily stored deep below the surface in mountainous areas is partly protected from atmospheric evaporation and transpiration. But in flat poorly-drained country, particularly when most of the underground-water remains near the surface within reach of the roots of trees, appreciable evaporation occurs during the storage period. Release of ground-water from protected parts of elevated catchment areas continues throughout the dry season, and then constitutes the principal source of river flow. The preponderance of water which has been protected from evaporation, thus reduces the chlorinity of the river water in dry periods, because flow from the lower and less efficient part of the catchment then becomes negligible, or entirely ceases. In the following wet season water stored in lower parts of the area, which had become more or less concentrated by evaporation during the dry season, is carried to the main river in the flow of intermittent tributaries, thereby making an appreciable addition to the salinity of the river water.

UPSTREAM STORAGE CAPACITY.

The rate at which water can be retained or released during an annual period appears to be limited; but unidirectional trends often persist for many years, in extreme cases for 20 years, before a reversal occurs on completion of a rainfall cycle. In the Goulburn area, during the period under review, six successive years, between 1919 and 1924, was the longest sub-period in which water was absorbed; depletion occurred during the following three years. Storage reached a maximum value in 1930 of 10·2 inches above datum. After a period of rapid depletion the value fell to 1·8 inches below datum, and remained almost constant for another seven years. The difference between the maximum and minimum values (12 inches) is equivalent to 960,000 acre-feet for the whole catchment, and it may be regarded as a preliminary estimate of the upstream storage capacity of the Goulburn area during the period under review. It is interesting to note that this volume is rather more than three times the present capacity of the Eildon Reservoir. A period of minimum storage was clearly reached between 1934 and 1940, but the catchment may not have been fully charged in 1930. Observations covering a longer period would be necessary before this question can be answered. Records extending for 50 years are available for the Mitta and Upper Murray River catchments, where the upstream storage capacities indicated are considerably higher. Rainfall distribution and other physical conditions would obviously affect the total storage capacity of a catchment area, and these differ from those prevailing in the Goulburn area. The possibility of being able to make even approximate estimates of the upstream storage capacities of catchment areas opens up an interesting field for further investigation.

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